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# The Home Care Crew Scheduling Problem

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**Abstract.** The Home Care Crew Scheduling Problem emerges in modern healthcare systems. The idea of home care is to offer a variety of services in the homes of the patients, whenever this is possible. A number of nurses and other personnel go from home to home and provide the necessary service. The Home Care Crew Scheduling Problem deals with the assignment of visits to caretakers and the scheduling of the visits. The objective of the mathematical optimization is to provide a higher level of service at a reduced cost. The problem is modeled as a set partitioning problem with side constraints and related to the vehicle routing problem with time windows, where this methodology has previously shown convincing results. The model is implemented using column generation in a Branch-and-Price framework and tested on four realistic test instances. The schedules generated are significantly better than the ones currently used in practice.
*Keywords: Crew scheduling, Home care, Vehicle routing, Temporal dependencies, Integer programming, Column generation, Set partitioning.*

## Introduction

The Home Care Crew Scheduling Problem (HCCSP) of this paper has its origin in the Danish healthcare system. The home care service was introduced in 1958 and since then, there has been a constant increase in the number of services offered. The primary purpose is to give senior citizens and disabled citizens the opportunity to stay in their own home for as long as possible. The HCCSP is the problem of scheduling caretakers in a way that maximizes the service level, possibly even at a reduced cost.

The methodology presented in this paper is built on the literature of the vehicle routing problem with time windows (VRPTW). Column generation has proven an invaluable tool in optimization of vehicle routing problems. The main differences to regular vehicle routing problems are a limited number of caretakers with individual shifts, temporal dependencies between visits, and the presence of a number of soft constraints. These exceptions must naturally be dealt with explicitly in the model.

The practical HCCSP presented here, has recently been addressed also by Justesen and Rasmussen [1], Lessel [2], and Thomsen [3]. This paper is based mainly on the work of Justesen and Rasmussen, where a Branch-and-Price approach is developed and applied. Lessel and Thomsen approach the problem with metaheuristics. Eveborn et al. [4] describe a system in operation in the Swedish home care system. Bredström and Rönnqvist consider a similar problem using an MIP model in a generic MIP solver [5] and using a set partitioning formulation in a Branch-and-Price framework [6]. Bertels and Fahle [7] describe a related problem from Germany. Cheng and Rich [8] present an MIP model and a two-phase heuristic with results for data instances from the United States. Begur et al. [9] describe a decision support system used also in the United States.

The remainder of this paper is organized as follows. First, we give a problem description emphasizing the challenges met in the concrete problem. Next, the solution method is described and with it, a mathematical model of the problem. The achieved results of the method are presented in the succeeding section. Finally, we present the main conclusions.

## Problem Description

When a citizen applies for home care service, a preadmission assessment is initiated. The result of the assessment is a list of granted services. The services may include cleaning and laundry assistance and support for other everyday tasks. They may also include assistance with respect to more personal needs, e.g. getting out of bed, bathing, dressing, preparing food, and dosing medicine. As a consequence of the variety of services offered, people with many different competences are employed as caretakers.

Given a list of services for each of the implicated citizens, a long term plan is prepared. In the long term plan, each service is assigned to specific time windows, which are repeated as frequently as the preadmission assessment prescribes. The citizens are informed of the long term plan, and hence they know approximately when they can expect visits from caretakers. From the long term plan, a specific schedule is created on a daily basis. In the daily problem, caretakers are assigned to visits. A route is built for each caretaker, respecting the competence requirements and time window of each visit and working hours of the caretaker. In the following, we restrict ourselves to look at the daily scheduling problem only.

The problem is a crew scheduling problem with strong ties to vehicle routing with time windows. However, we have a number of complicating issues that differentiates the problem from a traditional vehicle routing problem. One complication is the multi-criteria nature of the objective function. It is, naturally, important to minimize the overall operation cost. However, the operation cost is not very flexible in the daily scheduling problem. More important is it to maximize the level of service that we are able to provide. The service level depends on a number of different factors. Usually, it is very hard to fit all visits into the schedule in their designated time windows. Hence, some visits may have to be rescheduled or cancelled. In our solutions, a visit is either scheduled within the given restrictions or marked as uncovered. The manual planner will deal with uncovered visits appropriately. The main priority is to leave as few visits uncovered as possible. Also, all visits are associated with a priority and it is important to only reschedule and cancel less significant visits. Also, it is important to service each citizen from a small subgroup of the whole workforce, as this establishes confidence with the citizen. Another complication compared to traditional vehicle routing, is that we have shared visits. These are visits requiring the presence of more than one caretaker, and consequently each visit must be included in the route of several caretakers, where the interconnected visits must be synchronized.

## Solution Method

HCCSP as described above is decomposed and modeled as a set partitioning problem (SPP) with side constraints. An elementary shortest path problem with time windows (ESPPTW) is used for column generation. The SPP is denoted the master problem, and the ESPPTW correspondingly is the subproblem. This approach has presented superior results on VRPTW and the similarities to HCCSP are strong enough to suggest the same approach here. There is a vast amount of literature on column generation based solution methods for VRPTW, see e.g. Kallehauge et al. [10] for a recent literature review and an introduction to the method.

In the master problem, given a large set of feasible routes to choose from, one route is chosen for each caretaker. The integer programming model of the master problem is given in (1)-(6). Given is a set of caretakers, $K$, and each caretaker must choose a route from the set $R^k$. Together, the routes must cover as many visits as possible from the set $N$. Each of the routes is generated so it respects travel times, time windows, working hours, and competence requirements. The cost of each route is calculated as a combination of the quality of service and the actual transportation costs.

The model contains two sets of decision variables:

$$\lambda_r^k = \begin{cases} 1 \text{ if route } r \text{ is chosen for caretaker } k \\ 0 \text{ otherwise} \end{cases}$$

$$\Lambda_i = \begin{cases} 1 \text{ if visit } i \text{ is not covered by any caretaker} \\ 0 \text{ otherwise} \end{cases}$$

Each route has some characteristics, which are described by the parameters:

$$c_r^k = \text{ the cost of the route } r \text{ for caretaker } k$$

$$a_{ir}^k = \begin{cases} 1 \text{ if visit } i \text{ is included in route } r \text{ for caretaker } k \\ 0 \text{ otherwise} \end{cases}$$

$$t_{ir}^k = \begin{cases} \text{the starting time of visit } i \text{ in route } r & \text{if visit } i \text{ is included in route } r \text{ caret. } k \\ 0 & \text{otherwise} \end{cases}$$

To complete the model we also introduce a set of temporal dependencies. These are described by a set, $P$, of triplets: $(i, j, p_{ij})$. Each triplet represents a temporal dependency of the type: “Visit $i$ must be scheduled at least $p_{ij}$ minutes before visit $j$”. Synchronization of visits $i$ and $j$ is hence modeled by introducing two triplets: $(i, j, 0)$

and (*j*, *i*, 0). Separately, the two triplets represent the two constraints: “visit *i* must start no later than visit *j*” and “visit *j* must start no later than visit *i*”, respectively. Together, they hence enforce synchronization.

Finally, we have the parameter:

$\tilde{c}_i =$ the cost of leaving visit *i* uncovered

The HCCSP can now be solved by finding a minimum cost combination of routes, such that all constraints of the model are respected.

$$\min \quad \sum_{k \in K} \sum_{r \in R^k} c_r^k \lambda_r^k + \sum_{i \in N} \tilde{c}_i \Lambda_i \tag{1}$$

$$\text{s.t.} \quad \sum_{k \in K} \sum_{r \in R^k} a_{ir}^k \lambda_r^k + \Lambda_i = 1 \qquad \forall i \in N \tag{2}$$

$$\sum_{r \in R^k} \lambda_r^k = 1 \qquad \forall k \in K \tag{3}$$

$$\sum_{k \in K} \sum_{r \in R^k} t_{jr}^k \lambda_r^k - \sum_{k \in K} \sum_{r \in R^k} t_{ir}^k \lambda_r^k \geq p_{ij} \qquad \forall (i, j, p_{ij}) \in P \tag{4}$$

$$\lambda_r^k \in \{0,1\} \qquad \forall k \in K, \forall r \in R^k \tag{5}$$

$$\Lambda_i \in \{0,1\} \qquad \forall i \in N \tag{6}$$

(1) is the objective function. The total cost of the routes plus the cost of having uncovered visits is minimized. Cost of a route is mainly determined by the service level of the visits in the route. (2) ensures that all visits are either included in exactly one route or considered uncovered. All caretakers must be given exactly one route (3). Temporal dependencies between routes must be respected (4). (5) and (6) are the integrality constraints for the decision variables.

The model is solved in a Branch-and-Price framework. As the number of feasible routes is exponential in the number of visits, it is impossible to include all routes a priori. Instead, the most promising routes (columns) are generated dynamically in an iterative process. The master problem is LP-relaxed and the columns are generated based on a dual solution to the LP-relaxation. Further, to enable solution of the subproblem by the standard label setting algorithm, the constraints (4) are relaxed from the master problem. The relaxed master problem is now a regular set partitioning problem. The subproblem is an ESPPTW and is solved by label setting (see e.g. Chabrier [11]). Integrality and temporal dependencies are enforced by branching. See Justesen and Rasmussen [1] and Dohn et al. [12] for thorough descriptions of the method.

## Results

The method is tested on authentic test instances from two Danish municipalities. The results are compared to the current practice, which is based partly on an automated heuristic and partly on manual planning. We measure three quality parameters: Uncovered visits, constraint adjustments, and total travel time.

The uncovered visits are visits, where a caretaker has not been assigned in the schedule. In practice, this may imply that the visit is cancelled or that a substitute is called in and assigned to those uncovered visits.

Another way of dealing with an uncovered visit is to adjust the original constraints, so that we are able to fit the visit into the schedule anyway. Possible options are to: reduce the duration of the visit, extend the time window of the visit or extend the work shift of one of the caretakers. This is done a lot in practice. However, any of these adjustments will naturally decrease the overall quality of the schedule. In the presented solution method, we have chosen to keep all the original constraints intact, and let the constraint adjustment be a manual post-processing task. This decision is also supported by the fact that it is hard to put a quantitative penalty on all possible adjustments before solving. The number of constraint adjustments in our solution will hence always be equal to 0.

The total travel time is a straight forward measurement. The time is measured in minutes for all caretakers for the whole daily schedule. Minimizing the total travel time is not as important as minimizing the two other measurements, but a low travel time is naturally preferred. As more visits are included in the schedule, the total travel times may be slightly larger in our approach than what we see in the current practice.

The test results are summarized in Table 1.

| | | | Former best solution (Current practice) | | | Solution from Branch-and-Price | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Number of caretakers | Total number of visits | Uncovered visits | Constraint adjustments | Total travel time | Uncovered visits | Constraint adjustments | Total travel time | Run time |
| **hh** | 15 | 150 | 9 | 0 | 427 | 5 | 0 | 448 | 2044 |
| **ll1** | 8 | 99 | 11 | 26 | 256 | 6 | 0 | 280 | 69 |
| **ll2** | 7 | 60 | 1 | 10 | 155 | 0 | 0 | 141 | 3 |
| **ll3** | 6 | 61 | 0 | 25 | 311 | 1 | 0 | 128 | 39 |

**Table 1.** Test results for four authentic test instances compared to the results achievable by current practice.

The results clearly indicate that we are able to enhance the service level. There is a significant decrease in the number of uncovered visits and a truly dramatic decrease in the number of necessary constraint adjustments.

The constraint adjustments in the original solution cover both minor and major modifications. They are immediate consequences of the complexity found in the manual scheduling task. The manual planner cannot command all possible solutions of the entire schedule and hence has to introduce modifications in order to come up with a reasonable schedule. The manual planner is usually willing to accept a rather large number of alterations, as long as it creates a schedule without too many uncovered visits.

Figure 1 is a graphical representation of the Branch-and-Price solution to **ll1**. Time is running on the horizontal axis. Each visit is represented by a box. Each caretaker is represented by an underlying bar, depicting the shift of that caretaker. The boxes below the line are uncovered visits. The uncovered visits are subject to skill requirements and some caretaker/visit combinations are therefore disallowed.

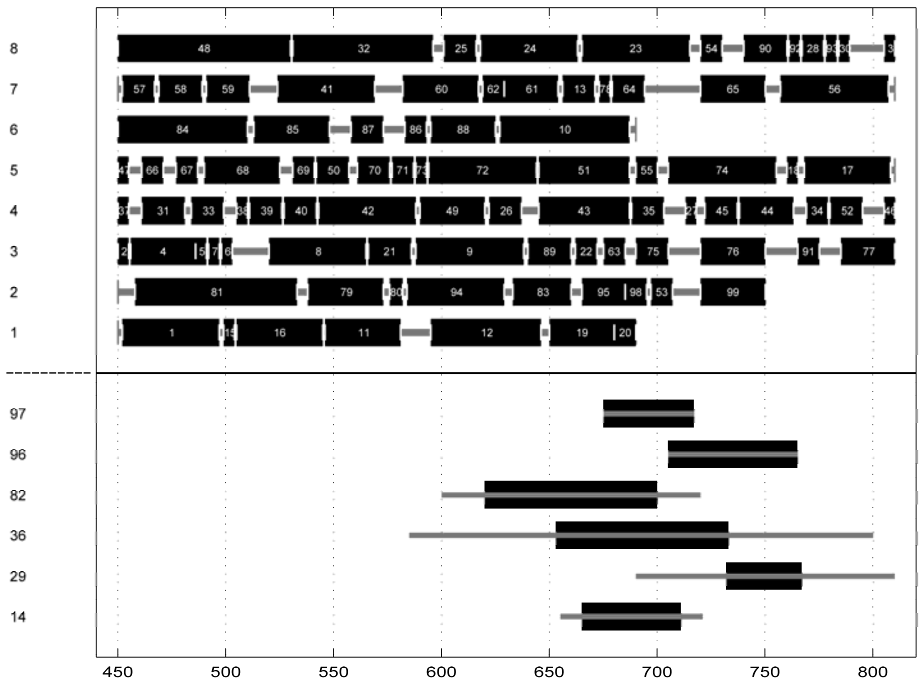


**Fig. 1.** Graphical representation of the Branch-and-Price solution to **ll1**.

Figure 2 visualizes the solution that was used in practice. The light gray visits have had constraints adjusted, e.g. the duration had to be reduced, or the visit had to be moved outside its original time windows. As seen in Table 1, this sums to 26 constraint adjustments. As also visible in Figure 2, we have 11 uncovered visits.

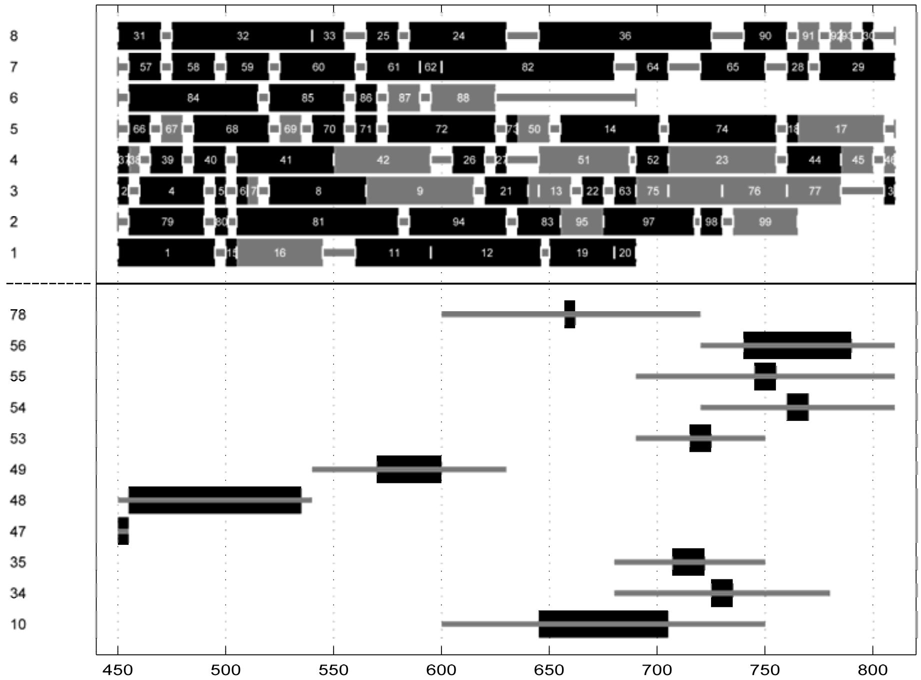

**Fig. 2.** Graphical representation of the former best solution to **ll1**.

## Conclusions

The Home Care Crew Scheduling Problem is a problem of great practical importance in the healthcare sector. The problem has been modeled mathematically as a set partitioning problem with side constraints. The model has a very large number of variables and hence these are considered implicitly using column generation in a Branch-and-Price framework.

The results for four authentic test instances are significantly better than the solutions currently used in practice. The results show that the mathematically based method is able to generate schedules of a high quality, where much less manual post-processing is needed.

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